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OPTICAL TECHNIQUES FOR SURFACE CHARACTERIZATION.(U)

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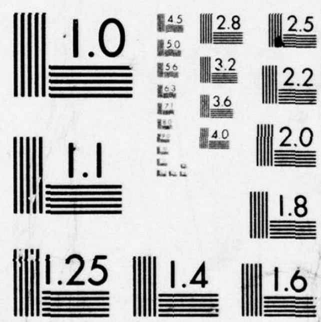

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FOR

ACE CHARACTERIZATION

FINAL REPORT

OPTICAL TECHNIQUES
FOR
SURFACE CHARACTERIZATION

FINAL REPORT

To
Army Research Office
Durham, North Carolina

For

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ABSTRACT

The available statistical analyses of laser speckle from smooth surfaces have been extended to account for the effect of anisotropic surfaces on the contrast and on the autocorrelation function. Experimental results are presented for comparison with the theoretical results. For rough surfaces, an experiment is proposed for remotely determining surface roughness by using two different illuminating angles. A significant aspect of the procedure is that photographic processing has been removed from the experiment so that the technique is of interest in radar applications. An extensive literature survey of methods for measuring correlation length is reported. The various techniques are classified into three categories, profilometric, optical, and photomicrographic. The most promising procedures are discussed and two techniques are recommended for laser radar research.

FOREWORD

Two graduate students contributed to the research reported here. They are E. M. Browne and D. L. Ellsworth. Their contribution is gratefully acknowledged, particularly, their fine work on correlation lengths. In addition, the facilities and expertise of the Laser Radar Laboratory, Physical Sciences Directorate, Army Missile Command, Huntsville, Alabama, were graciously made available to us by Dr. E. L. Wilkinson. We are grateful for this and, especially, grateful for the help of Dick Lattanzi in the area of signal processing and computer control of the experiments, and for the help of Ron Sartain in acquiring suitable surfaces.

SMOOTH SURFACES

Introduction

For the purposes of speckle statistics, a surface is considered smooth if it has an rms surface height variation much less than the wavelength of the illuminating radiation. Two important statistical parameters of the speckle intensity produced by laser radiation scattered from such surfaces are the contrast and the autocorrelation function. An experiment to measure these parameters for the surfaces having different surface roughness has been performed. The experimental arrangement and the results are presented in the following section. The surfaces are typical man-made surfaces in that lines are evident. Previous theoretical analyses have only considered surfaces that have statistics that are circular. Thus, it is significant to report the successful extension of the available analyses to include the effect of lines in the surface, that is, surfaces with non-circular statistics. This analysis is presented in the section on theory.

Two topics have been considered in addition to non-circular surface statistics. These are:

(1) The effects of using a beam with a gaussian intensity variation in the transverse plane.

(2) The effects of being in the far field of the illuminated target.

The far field results are of primary interest in a laser radar application. These additional topics are also contained in the section on theory.

Experiment

Experiments were conducted to measure the statistics of the speckle produced by surfaces from a set of surface texture standards. The work was performed at the Laser Radar Laboratory of the Army Missile Command, Huntsville, Alabama, during the Summer, 1975. The surfaces were illuminated with a laser beam and the resulting speckle patterns were sampled by a photodetector. Figure 1 shows the experimental arrangement that was used, and Figures 2 and 3 show typical results from relatively smooth and relatively rough surfaces. One statistical parameter that can be used to distinguish speckle patterns is the contrast. The contrast is defined as the ratio of the standard deviation of the signal to the mean value of the signal. As examples, the data presented in Figures 2 and 3 yield contrasts of 0.49 and 0.91, respectively.

The data presented in Table 1 summarizes the results of measuring the contrast of the speckle from the different surfaces. The surfaces were from a set of texture standards so that different rms surface deviations were represented. All of the surfaces had lines in the surfaces so that the speckle was found in a pattern approximately 3 cm wide by several cm long. The first column of contrast values in Table 1 was obtained by sampling the speckle pattern across the pattern (along the 3 cm dimension), whereas the second column represents contrast values obtained by sampling along the pattern. There is little difference indicated between the two columns of data.

Another important statistical quantity that can be associated with a speckle pattern is the autocorrelation function. Thus, the

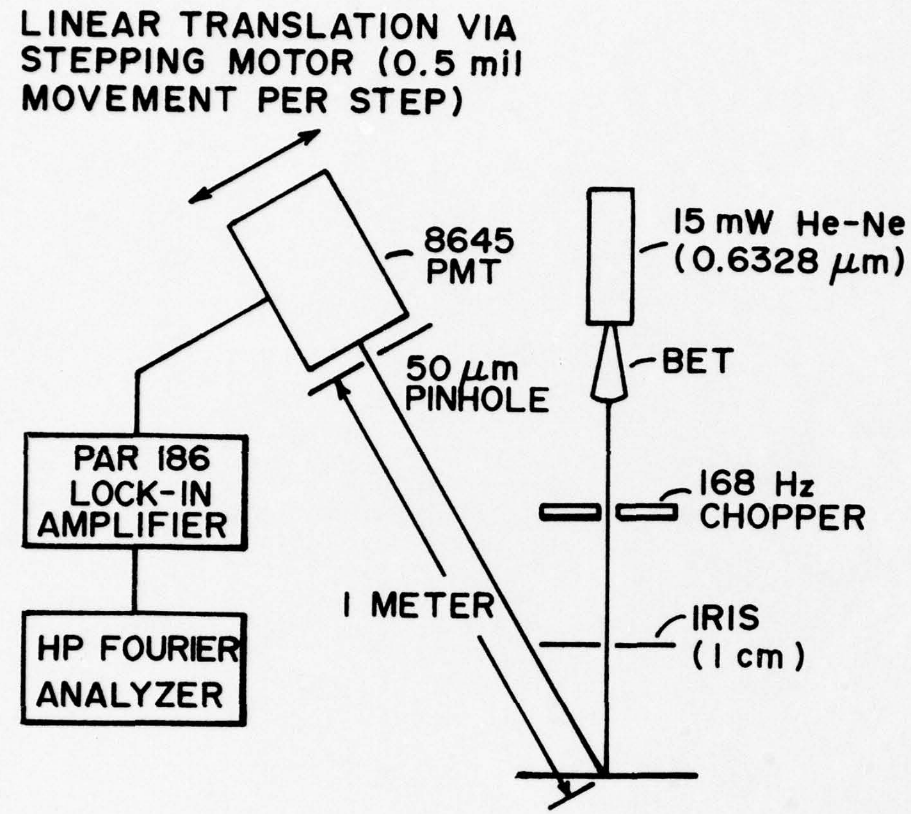

Figure 1

The arrangement shown was used to determine the statistics of speckle scattered from surface texture standards (M-15 set, GAR Electroforming Division, MITE Corporation).

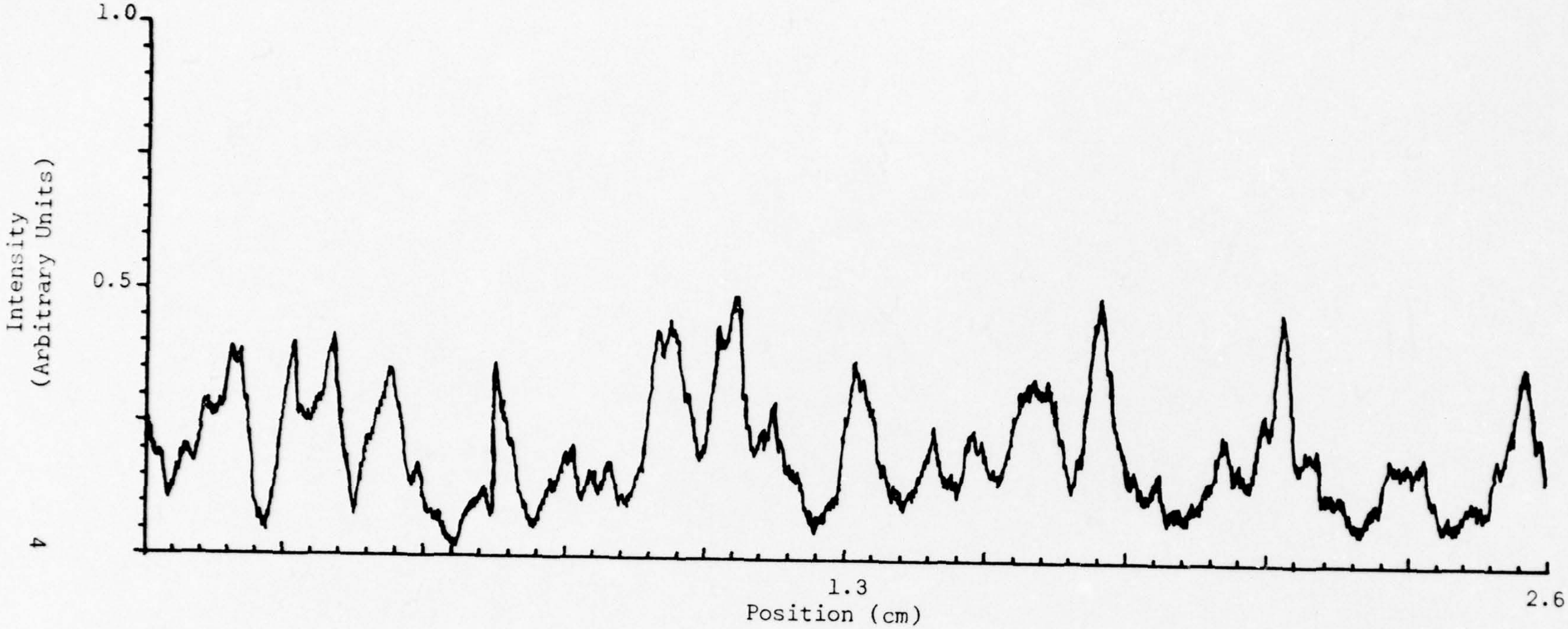

Figure 2

A composite of four scans across the speckle pattern produced by a 2 microinch rms roughness texture standard is shown. The direction of the scan is along the smaller dimension of the pattern.

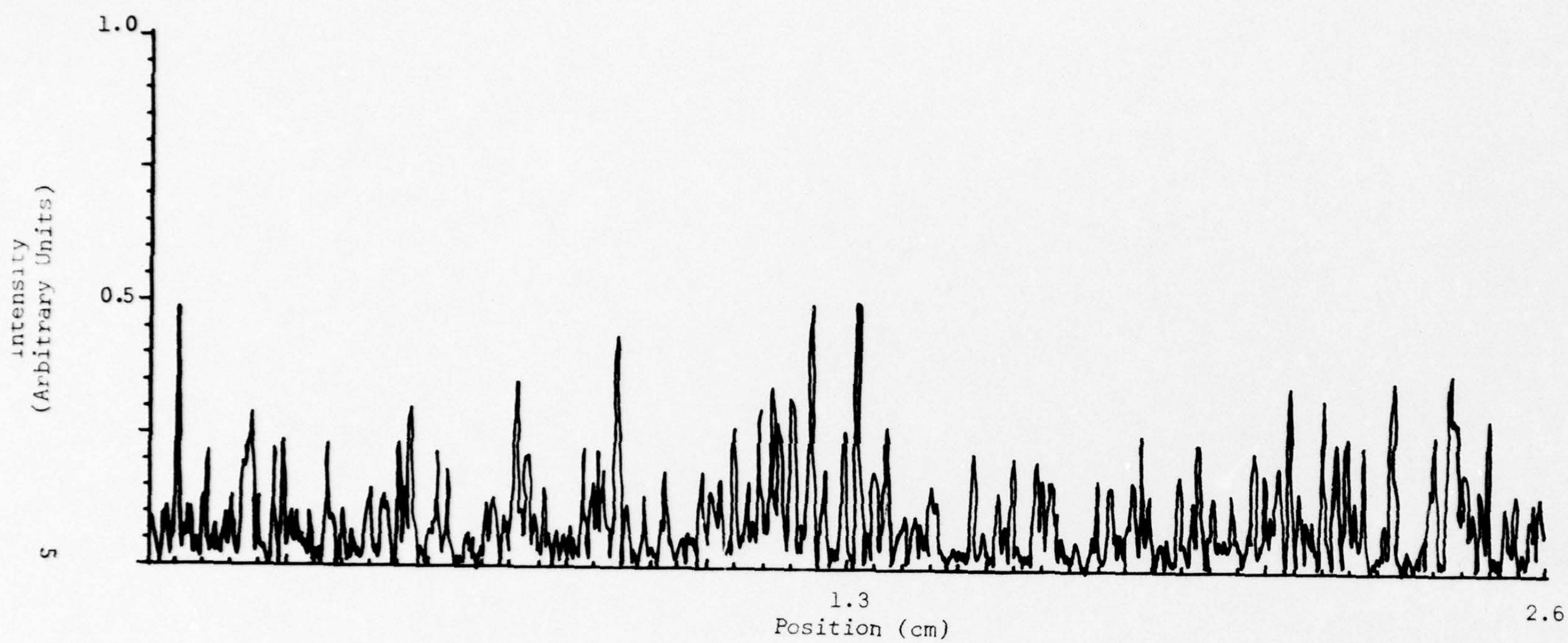

Figure 3

A composite of four scans through the speckle pattern produced by a 32 microinch rms surface roughness texture standard is shown. The direction of scan is along the longer dimension of the pattern.

SURFACE	CONTRAST 1	CONTRAST 2
2	0.49	0.58
4	0.47	0.51
8	0.79	0.76
16	0.81	0.90
32	-	0.91

Table 1

Table 1. Contrast values are reported for the speckle patterns produced by various surface texture standards. The overall speckle pattern was not circular so that the first column of values is for detector scans along the smaller dimension of the pattern, and the second column of values is for scans along the larger dimension. The value shown is generally the average of the four lowest values obtained from a group of eight or more scans. An average for all of the scans would be larger than the values shown here by 0.05 to 0.10.

autocorrelation function was determined for the speckle pattern from each surface listed in Table 1. Typical results are shown in Figures 4 and 5 for relatively smooth and relatively rough surfaces. The "-1" and "-2" refer to columns 1 and 2 in Table 1 and, therefore, represent different directions of sampling with the photodetector. Again, no consistent differences exist between the autocorrelation functions for the two sampling directions.

Theory

The principal experimental results presented in the previous section can be explained by extending available analyses of speckle statistics. Those analyses have considered laser light scattered from surfaces that were isotropic, that is, surfaces with height variations that were described by circular statistics. Many surfaces, including those studied in this project, have lines evident so that their statistical description is anisotropic. Thus, the extension of the previous analyses is an important one from a practical viewpoint. The additional topics of gaussian illuminating beam and far field effects are dealt with at appropriate points in the present analysis.

An analysis of the dependence of speckle contrast on surface roughness by Goodman [1] closely matches the experimental situation being discussed. Goodman treats surfaces with circular statistics so that the approach here is to extend that work at appropriate points to account for anisotropic surfaces. Referring to Figure 1, let (x_1, y_1) define points on the surface and (x, y) define points in the plane of the photodetector. The phase of the reflected light is modified so that it is given by $\Theta(x_1, y_1) = (2\pi/\lambda)\ [(1 + \cos \beta)]\ h\ (x_1, y_1)$ where $h\ (x_1, y_1)$

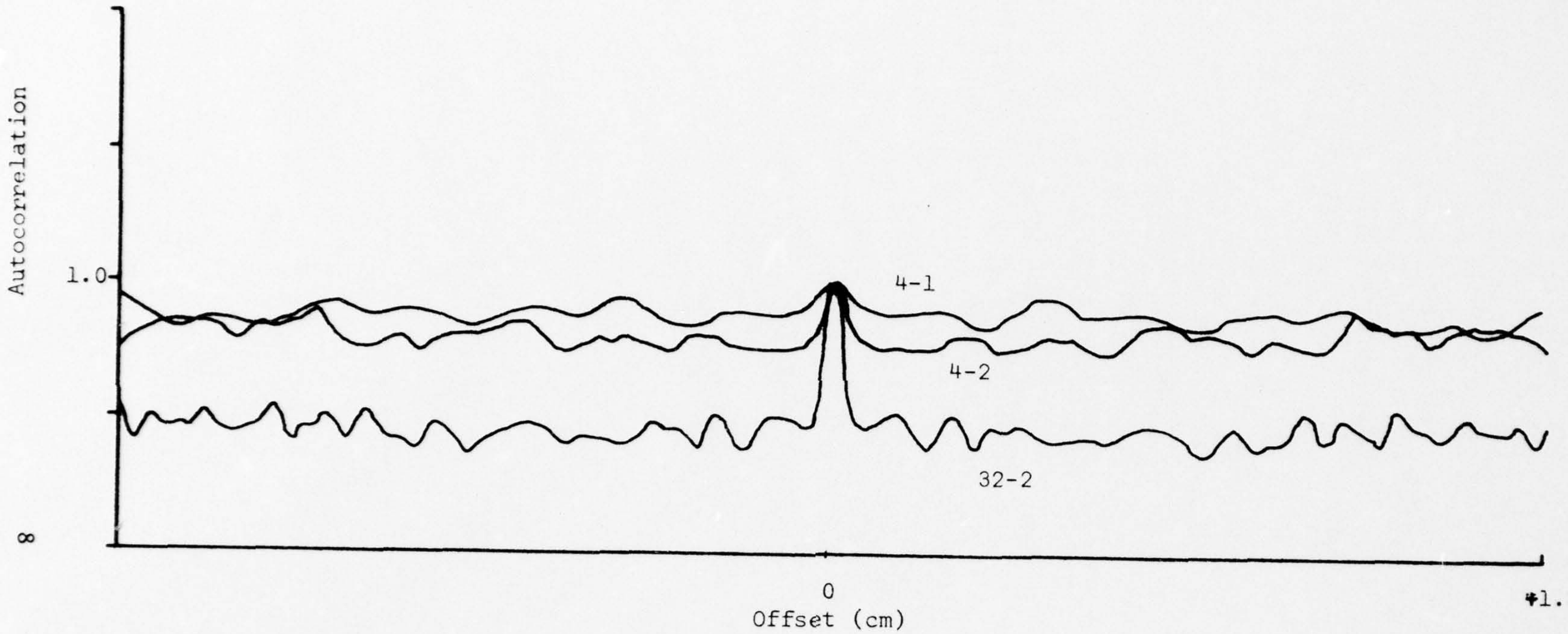

Figure 4

The autocorrelation functions are shown for the speckle produced by a smooth surface (4 microinch rms surface roughness). A similar result for a rough surface (32 microinch rms surface roughness) is shown for comparison. The speckle pattern was not circular so that the curves labelled "-1" and "-2" represent detector motion along the short dimension and along the long dimension, respectively.

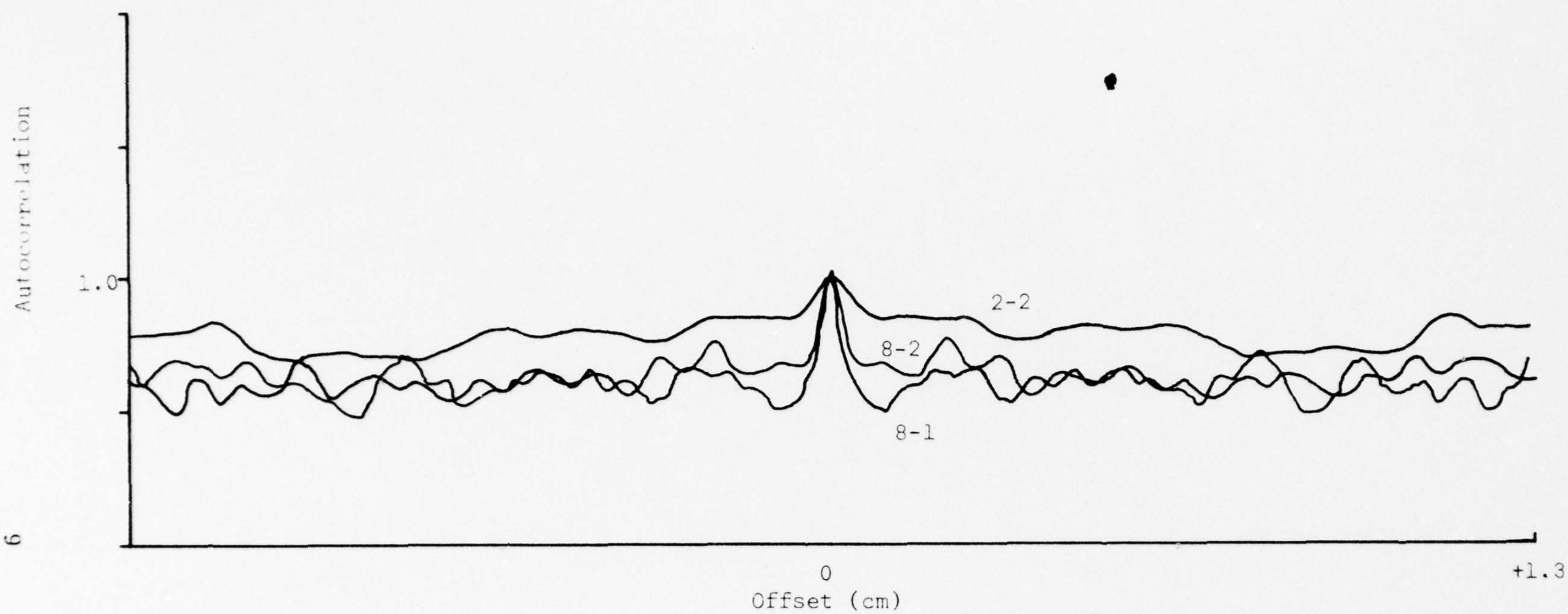

Figure 5

The autocorrelation functions are shown for the speckle produced by a rough surface (8 microinch rms surface roughness) with a similar result for a smooth surface (2 microinch rms surface roughness) shown for comparison. The labels are explained in Figure 4.

is the surface height above its mean plane, β is the angle between incident and reflected specular beams and λ is the wavelength of the laser used. The angle β was always less than 10 degrees so that cos β will be approximately equal to 1. Thus, the reflected field is assumed to be of the form

$$a(x_1, y_1) = \exp[j(4\pi/\lambda)h(x_1, y_1)]$$

and the field at the photodetector is given by

$$A(x, y) = \iint_{-\infty}^{\infty} K(x - x_1, y - y_1)\, a(x_1, y_1)\, dx_1 dy_1$$

K represents the impulse response of the optical system between the surface and the photodetector. Thus, differences in optical systems affect only the function K so that Goodman's results can be used [1]. Far field effects are implicitly included because the function K can be chosen appropriately.

The significant results are contained in Goodman's Equations 9-12. These results are repeated here for easy reference. The field at the photodetector is written as the sum of a real part, A^r, and an imaginary part, A^i. Goodman shows that

$$\langle (A^r)^2 \rangle = \exp(-\sigma_\theta^2) \iint_{-\infty}^{\infty} k(\Delta x_1, \Delta y_1) \cosh[\sigma_\theta^2 \rho_h(\Delta x_1, \Delta y_1)]\, d\Delta x_1\, d\Delta y_1$$

$$\langle (A^i)^2 \rangle = \exp(-\sigma_\theta^2) \iint_{-\infty}^{\infty} k(\Delta x_1, \Delta y_1) \sinh[\sigma_\theta^2 \rho_h(\Delta x_1, \Delta y_1)]\, d\Delta x_1\, d\Delta y_1$$

$$\langle A^r A^i \rangle = 0$$

where

$$k(\Delta x_1, \Delta y_1) = \iint_{-\infty}^{\infty} K(x_1, y_1) K(x_1 - \Delta x_1, y_1 - \Delta y_1)\, dx_1 dy_1$$

In the above, <> indicates ensemble averaging, σ_Θ^2 is the variance of the phase and ρ_h is the correlation function of the surface. Further results from Goodman [1] are

$$\sigma_r^2 = S_p \exp(-\sigma_\theta^2) \iint_{-\infty}^{\infty} \{\cosh[\sigma_\theta^2 \rho_h(\Delta x_1, \Delta y_1)] - 1\}\, d\Delta x_1\, d\Delta y_1$$

$$\sigma_i^2 = S_p \exp(-\sigma_\theta^2) \iint_{-\infty}^{\infty} \sinh[\sigma_\theta^2 \rho_h(\Delta x_1, \Delta y_1)]\, d\Delta x_1\, d\Delta y_1$$

where σ_r^2 and σ_i^2 are the variances of A^r and A^i respectively, and Sp is the pupil area.

At this point it is convenient to depart from Goodman [1] by choosing ρ_h to be appropriate for a surface with lines in evidence. A two-dimensional gaussian function is chosen with two independent correlation lengths. The experimental results that the speckle pattern was generally elliptical supports the use of two correlation lengths. Thus, the correlation function for the surface is

$$\rho_h(\Delta x_1, \Delta y_1) = \exp[-(\Delta x_1/x_c)^2] \exp[-(\Delta y_1/y_c)^2]$$

where x_c and y_c are the correlation lengths for those directions. Expanding the hyperbolic cosine and sine in a power series and integrating term by term results in

$$\sigma_r^2 = S_p \pi x_c y_c \exp(-\sigma_\theta^2) \sum_{n=1}^{\infty} \frac{(\sigma_\theta^2)^{2n}}{2n(2n)!}$$

$$\sigma_i^2 = S_p \pi x_c y_c \exp(-\sigma_\theta^2) \sum_{n=0}^{\infty} \frac{(\sigma_\theta^2)^{2n+1}}{(2n+1)(2n+1)!}$$

Comparison with Goodman [1] indicates that by defining $N = (S_p\ \pi\ x_c y_c/\lambda z)^{-1}$, Goodman's expression for contrast can be used. Also, Goodman's Figure 2 can be used for plots of contrast versus $\sigma_\Theta/2\Pi$ with N as parameter. Since N is the effective number of

correlation areas, one can conclude that lines in a surface simply change the correlation area. This is in agreement with the data presented here that indicates approximately the same value of contrast regardless of the sampling direction. It is also apparent from this analysis that the contrast saturates at its rough surface value for surfaces whose rms surface height variation is greater than $\lambda/2$ for the conditions of the experiment. Thus, good agreement between theory and experiment has been achieved as far as contrast is concerned.

A general theoretical analysis of the experimental autocorrelation function results can be found in Goodman [2]. As pointed out there, for circular gaussian fields the autocorrelation function is simply related to the mutual intensity function defined by

$$M(x,y;x',y') = \langle A(x,y)\, A^*(x',y') \rangle$$

where (x, y) and (x', y') denote points in the plane of the photodetector. It is often convenient to use a normalized form of the mutual intensity known as the complex coherence factor,

$$m(x,y;x',y') = \frac{M(x,y;x',y')}{[M(x,y;x,y)\, M(x',y';x',y')]^{1/2}}$$

Goodman [2] shows that for the far field case, the mutual intensity is given by

$$M(x,y;x',y') = k\,(\lambda z)^{-2} \iint_{-\infty}^{\infty} |P(x_1,y_1)|^2$$

$$\exp[j(2\pi/\lambda z)(x_1\Delta x + y_1\Delta y)]\, dx_1 dy_1$$

$$\iint_{-\infty}^{\infty} m(\Delta x_1,\Delta y_1) \exp[j(2\pi/\lambda z)(x'\Delta x_1 + y'\Delta y_1)\, d\Delta x_1 d\Delta y_1$$

In this expression, $|P(x_1, y_1)|^2$ represents the intensity distribution of the illuminating beam, Δx and Δy are $x_1 - x_2$, and $y_1 - y_2$, and Δx_1 and Δy_1 are separation distances between two points in the plane of the

surface. The first Fourier transform in the expression above represents a narrow function characteristic of speckle. The second Fourier transform represents a broad function corresponding to a distribution of average intensity over the photodetector plane.

Thus, as Goodman [2] notes, the correlation function of the field at the surface affects only the size of the pattern scattered from the target. It does not affect the speckle coarseness. This is in agreement with the experimental results that indicate nearly identical autocorrelation functions for the speckle when sampled along different directions. However, the surface correlation function not being circular does cause the overall pattern to be elliptical rather than circular. The use of a gaussian illumination beam would not change these arguments. Then, it can be concluded that Goodman's analysis provides an adequate theoretical explanation of the experimental results.

Conclusion

Satisfactory agreement is evident between the theory presented here and the experimental results. Available analyses have been extended to include the effect of surfaces with lines, that is, surfaces with non-circular statistics. It is apparent from the results presented here that the correlation function for the surface affects the distribution of average intensity scattered from the surface. However, the contrast and autocorrelation functions for the speckle produced are not sensitive to the surface correlation function.

Additional studies are indicated in two important areas. The optical system was treated in the case of contrast studies by using the system's impulse response. Goodman [1] makes the assumption that the optical system's impulse is a real function. There are many important

systems for which this is not true. Consequently, some effort should be devoted to the study of the effect of a complex impulse response on the relationship between speckle contrast and surface roughness. Another topic that warrants further study concerns the autocorrelation function. The analysis presented here assumes that fields in the photodetector plane are circular gaussian so that a simple relationship exists between the autocorrelation function and the mutual intensity. However, for very smooth surfaces the scattered fields are not circular gaussian [1]. Thus, it would be of interest to determine the autocorrelation function for fields that are not circular gaussian. This would be particularly important in experiments involving longer wavelength lasers such as carbon dioxide lasers. For these longer wavelengths, more surfaces would appear to be very smooth relative to the illuminating radiation wavelength.

STUDY OF RELATIVELY ROUGH SURFACES

Introduction

There has been considerable discussion in the literature concerning the possibility of using speckle statistics for determination of surface properties of relatively rough surfaces [3-5]. It has been concluded that statistical analysis of a single speckle pattern cannot be used as a general method for determining surface roughness; however, processing of two speckle patterns has been used to measure surface roughness for relatively rough surfaces[6].

The two speckle patterns were produced by illuminating the surface at two different angles. The speckle patterns were recorded on film in such a manner that Young's fringes were produced when the developed film was illuminated by a converging beam. The visibility of these fringes was measured as a function of surface roughness and the angular difference between the two illuminating beams. Thus, a measurement of the visibility for a specific angular difference was used to determine surface roughness. The experimental procedure was as follows:

(1) One pattern was used to expose the film.

(2) The angle of illumination was changed.

(3) The film was shifted by the amount of the pattern shift.

(4) The second pattern exposed the same film as the first pattern.

(5) The film was developed and then placed in a converging beam.

(6) Visibility of Young's fringes was measured.

This approach proved successful and good agreement between theory and experiment was attained. The major disadvantage of this method is that photographic processing is a necessary step in the procedure.

The research effort in this area has been to define an experiment in which the photographic process can be replaced with a photodetector and digital computer. It should be noted that the computer will operate on information from scans of the speckle pattern and will not produce the same amount of information as is contained on the photograph. The parallel processing inherent in the photographic process produces a large amount of information. Some of this information was not used since the fringe visibility was measured with a scanning slit and photodetector placed near the center of the illuminated region. It should also be noted that the photographic process does not require recording of phase information as is true in many holographic techniques. Therefore the photodetector should be adequate to record the intensity information that is necessary.

Analysis

A first step in outlining the experiment was to study the signal processing involved in the photographic process so that the necessary processing could be specified for the computer. Perhaps the key equation in the work by Leger, et al. [6], is their Equation (14) for the visibility of the fringes. This equation is given below:

$$V = \frac{2\langle I(\nu_z, \nu_z')\rangle}{\langle I(\nu_z, \nu_z)\rangle + \langle I(\nu_z', \nu_z')\rangle}$$

In the work by Leger, et al., these quantities are expressed in terms of the field distribution across the surface of the test specimen. However, the signals that will be available for computer processing are the reflected intensities from the rough surfaces. Therefore, it was necessary to relate these quantities directly to the intensities of the speckle patterns. Leger, et al., note that the two terms in the denominator represent the power spectral density functions of each speckle pattern and the numerator term is a function of the correlation between the two speckle patterns.

Our analysis of the functions involved showed that the terms in the denominator could be obtained by taking the Fourier transform of the respective intensity patterns and multiplying each transform by its conjugate, thus yielding the power spectral density functions. It is also possible to obtain these by taking the Fourier transforms of the autocorrelation functions of the speckle patterns. We were also able to show that the numerator term is proportional to the Fourier transform of the cross correlation of the two speckle patterns. Standard computer programs are available that will perform the operations above and therefore, it should be possible to use the computer to generate a function which corresponds to the visibility of the fringes.

Experimental Outline

The following experimental procedure is suggested as an alternate to the photographic technique.

(1) Illuminate the surface with a beam at a known angle. Sample the speckle pattern with a photodetector and positioning system such that the speckle is resolved and an adequate number of samples are

obtained. The beam size and distance from surface to detector should be adjusted so that the Fraunhofer approximation is valid. Experimental limitations may require the use of a lens to insure this condition is satisfied. The photodetector output is to be converted to digital form and placed in the computer for processing.

(2) Change the angle of illumination, shift the photodetector by the amount of the pattern shift and repeat step(1).

(3) Use the computer to compute the denominator and numerator terms of the visibility function. It is anticipated that multiple scans may be necessary in step (2) in order that the cross correlation for the numerator term may be maximized.

(4) Use the information from step (3) to form the visibility function by taking the appropriate transform, adding the denominator terms and dividing into the numerator. Leger, et al., show visibility as a single number rather than a function. This was done by choosing fringes near the center and measuring visibility. Thus, a number for visibility in (4) may be obtained by using the peak value obtained in step (4).

Leger, et al., have shown theoretically that visibility may be related to rms surface roughness σ and beam angular difference $\delta\Theta$ by

$$V = \exp\left\{\left[(2\pi/\lambda)\,\sigma \sin\theta_1\, \delta\theta\right]^2\right\}$$

where λ is the wavelength of the incident radiation and Θ_1 is the angle of incidence of the first beam. Experimental agreement with the

expression was achieved with photographic determination of V. Evaluation of the computer determination of V may be accomplished by performing the experiment that has been outlined and comparing the values of V with those predicted by the theoretical expression.

Conclusions

In conclusion the analysis of the processing steps involved has indicated that it should be feasible to determine fringe visibility by use of a computer and thereby eliminate the photographic processing. Elimination of photographic processing is essential if this method is to be adapted for use in a laser radar system.

Additional studies in this area could be very fruitful for laser radar applications. A basic requirement of this technique is that two speckle patterns be available for analysis. The two different patterns are obtained by changing the illumination angle a small amount. It is apparent in a radar situation that a translating target could be viewed at different times to provide this angular change. Thus, the basic requirements for this technique of detecting surface roughness would be satisfied. However, an analysis of a spinning, nutating target would have to be conducted to determine the signal analysis requirements.

Other approaches that warrant investigation are different techniques for achieving the angular change. Among these would be the use of two beams simultaneously with a single detector, or the use of a single beam with two detectors separated an appropriate distance.

SURFACE ROUGHNESS CORRELATION LENGTH

Introduction

A single parameter is not always sufficient information about surface height variations. The rms surface height variation for a random surface and for, say, a sinusoidally varying surface height could easily be the same value. Yet, for many applications the two surfaces are not equivalent. Thus, in many applications a quantity called surface roughness correlation length is necessary (along with rms roughness) to adequately characterize a surface. The available techniques for measuring surface roughness correlation length have been surveyed by doing an extensive literature search on this topic.

The principal techniques used have been classified into three categories, profilometric, optical, and photomicrographic. Emphasis was placed on techniques that required a minimal amount of specialized equipment. The discussion here centers on what seems to be the most promising techniques from each category rather than attempting to list all possible variations. Often, the rms surface roughness is involved in the determination of correlation length so that the measurements are not always independent. Also, the technique used by Leger, et al. [6], is discussed extensively elsewhere in this report and, therefore, is not included in this section.

Profilometric Techniques

Profilometry is the simplest and most common method for obtaining characterization of surfaces. A mechanical profilometer has a fine-tipped stylus which is drawn mechanically across a sample surface. This

movement yields a vertical motion of the stylus that is sensed electrically and amplified to yield a surface profile trace. The vertical scale of the trace is highly magnified relative to the horizontal scale. In order for the output to be most useful the analog electrical signal from the profilometer must be changed to digital form and processed by a computer [7].

Thomas [8] gives computer formulas for the autocorrelation function and other statistical parameters which may be determined under the assumption of a gaussian distribution of heights for the surface. However, Williamson [9] has found that usually only the middle 90% of a random surface is gaussian. Once the autocorrelation function has been obtained, the correlation length can be determined. The correlation length gives a measure of the rapidity with which the autocorrelation function decays from its peak value. Whitehouse and Archard [10] and also Thomas [8] define the correlation length as the half-width between points where the autocorrelation function is ten percent of its maximum value. Peklenick [11] uses this same definition and also a correlation distance where the autocorrelation function has decreased to 50% of its maximum value.

To obtain three dimensional representations of the surface, the profilometer may be allowed to trace in the x and then in the y directions or the trace may be done radially while allowing the sample to rotate. The second approach may yield more than just time savings. Peklenik [11] has found anisotropic regions in the surface by using a polar plot of correlation length. These regions appear as variations in a circle. The disadvantage of the radial trace is that the accuracy of the surface

definition decreases in proportion to the distance from the pivot point for fixed rotation rate.

Potential sources of error exist because of the physical nature of the instrument. Since the stylus has a finite dimension it will not maintain surface contact for deep narrow cracks and it may not respond to extreme changes in slope. Since the extremes may not be followed, a function of any surface as measured by profilometry may appear to be gaussian distributed when it actually is not. Williamson [9] used a profilometer for his work and found the extreme ten percent surface deviations to be non-gaussian. The question arises as to how much the stylus altered his results. This problem may be minimized by using a smaller tip, but this may increase the probability of scratching or altering the surface. Another problem can arise if a surface has a repetitive pattern. This may lead to an erroneous correlation length unless filtering is used to remove this pattern. If the filtering is performed on the analog signal, phase variations may distort the frequencies near the passband [12]. It is possible to use digital filtering of the data after it has been supplied to the computer and avoid this problem.

Optical Techniques

Profilometric techniques require mechanical contact with the surface being studied. This contact can result in scratches, thus changing the test surface. Optical techniques have the inherent advantage of not disturbing the surface. Furthermore, from a laser radar viewpoint it is preferable to determine surface parameters in much the same manner as they will be detected. Effects such as shadowing are

then duplicated so that a more accurate signature of the surface is obtained. It may not be a true profile, but it is a more appropriate measurement technique for radar applications. This section presents some of the important optical techniques for determining correlation length for surfaces.

Fujii, et al. [13], have reported an experimental study of the contrast of speckle produced from surfaces illuminated by a laser. The experiments established a relationship among the average contrast of the speckle patterns, the surface parameters consisting of rms surface roughness and correlation length, and the illuminated area of the surface. The laser beam was focused onto a very small area of the surface which was slowly translated perpendicular to the beam. A photodetector in the Fraunhofer region sensed the variations of the intensity, i.e., sampled the speckle pattern. A statistical analysis of the signal from the photodetector yielded the average contrast, V, of the intensity variations. The experimental observations established a dependence of V on the beam waist (diameter of the illuminated spot), w, the rms surface height variation, and the correlation length, a. Their work indicates that a plot of V versus w exhibits a maximum at w = a. The phenomenon of V decreasing with increasing w is expected from the theoretical work of Pedersen [14] and Goodman [1], but the increase of V for increasing w with w<a is apparently an unexplained experimental result. It appears to be an exceptionally useful observation in terms of optically measuring the correlation length of a surface.

Nagata, et al. [15], evaluate the degree of coherence variation of reflected radiation as a function of beam spread, roughness, and correlation length. At one point they mention the relationship between

beam spread and speckle contrast which, as noted above, has been shown [13] to be useful in measurement of surface parameters. However, their main thrust is that for a given beam spread, coherence decreases with increasing correlation lengths. In the limit of an infinite beam spread, the coherence approaches a constant.

Nagata, et al. are able to find rms roughness and correlation length by a process of determining the various unknowns in their equations individually. It is shown that when e, the space between two points situated symmetrically about the axis, is much larger than the correlation length, the coherence reaches a constant value given by exp $(-g^2)$ so that the constant g can be estimated. By using this value, the correlation length is found from the value of coherence obtained at small values of e (some values less than the correlation length). Both rms roughness and correlation length can then be estimated. In practice, g is the mean of the coherence value for several values from e.

Hildebrand and Gordon [16] have developed an instrument for determination of surface characteristics based on a measurement of the relative magnitudes of light scattered from a standard and a test surface. Although the theory of the data reduction depends upon gaussian statistics, the authors have obtained good results even with non-gaussian surfaces. Their paper describes the instrument, its theory and experimental results of its usage.

The measurements yield values for rms roughness but the assumption is made that the test surface and the standard surface have approximately the same correlation length. For the purposes of determining correlation length the reverse assumption must be true

or the rms roughness for each of the two surfaces under comparison must be known. With this assumption, the equations reduce in a manner similar to the previous case and correlation length may be determined. The theory upon which this instrument is based comes from the equation for scattering from a rough surface possessing gaussian statistics as derived by Bennett and Porteus [17]. Since most surfaces were found to be non-gaussian, it was necessary to take an angular average of the quantity Ω (Θ) defined by the ratio of sample and standard irradiances. This quantity should remain constant with angle Θ for gaussian surfaces, but due to deviations in the surface statistics, it may not. This fact could possibly be used with the instrument to evaluate the nature of the statistics of a surface under consideration.

Berny and Imbert [18] discuss an "optical profilomter" using coherent optics. A chopper modulated laser is directed through an objective lens onto a sample surface at some angle θ from normal. The specular reflection is directed by a mirror through a pinhole and second objective lens to focus on a photo diode connected electrically to a synchronous detector. By choosing Θ to obtain the peak intensity in the specular direction and applying relationships involving the same intensity ratios and expressions used by Hildebrand and Gordon [16] (from Bennett and Porteus [17]), the diffuse component may be separated from the expression for peak radiation. The diffuse component will be minimal for smooth surfaces at angle Θ (specular angle) and large for rough surfaces, with a corresponding decrease in the peak component.

To find the correlation length, T, of rough surfaces (those with rms roughness greater than 2μm) an expression is used which involves pupil radius and other system constants as a function of the above mentioned intensity ratio. Again, gaussian statistics have been assumed and such phenomena as "blazing" (as in a grating) or other regularities in the surface which might shift the radiation peak away from the specular angle are not permitted. (A more general theoretical treatment of surfaces with other statistics is given by J. C. Leader [19, 20, 21], and intensity dependency on angle and wavelength is derived.) Essentially, it is assumed that the rough surface is sufficiently rough for the specular peak to disappear. For the smooth surface this assumption obviously cannot be made because of the high degree of specular return. The general equation must be used, this time with the diffuse component assumed zero (again with Θ chosen for peak return at specular angle). If neither assumption can be made, the method is not valid. The instrument can be used to calculate simultaneously both rms roughness and correlation length, T. The precision can be increased by any method which will increase the accuracy of the determination of the rms roughness, since T is determined from this value. For smooth surfaces, T values within 3-5% of mechanical profilograph values have been obtained.

In a related paper, George [22] discusses the utilization of a frequency modulated coherent source to characterize surface features. The scattering of monochromatic radiation by rough surfaces gives rise to speckle patterns of varying contrast. Smooth surfaces or surfaces where the angle of incidence of the radiation is increased toward grazing produce lower contrast speckle than rough surfaces

or cases of more nearly normal incidence. These effects have been used to sense surface texture remotely.

With polychromatic light, the speckle becomes less distinct and this fact has also been exploited in measuring surface properties. It appears that tunable laser sources are well suited to remote sensing of shape features. In conceptual terms, the tunable laser under programmable control can be used to provide an inverse to Fourier transform spectroscopy. Thus, instead of measuring some particular source's spectral profile by controlled mirror motion, one can establish some measure of an unknown object's profile by Fourier analysis of the scattered return which is recorded as a laser is scanned in wavelength. There are two aspects of the method which may be worthy of note. A rough body will tend to have an appreciable return from all points on its surface while a smooth body will produce a return only at specular angles. Furthermore, the profile or depth features of an object will dominate the functional form of the cross-correlation between patterns produced by small wavelength offsets. (For a discussion of decorrelation with wavelength, see Elbaum, et al. [23]). It is thus indicated that an experimentalist could develop an FM laser technique for surface feature sensing in which depth profiles are measured with relative independence to variations in surface texture. This can be called a surface correlation length measurement if desired, although the length refers to that of the large scale surface characteristics and not of the microscopic texture. In some instances, such a characterization may yield more useful information than an analysis of an object's texture. The two types of measurement are to be compared to the bandpass selection

done for a profilogram. If low frequency signals are not filtered out, the computer correlation length will reflect the macroscopic surface features rather than the textural characteristics.

Photomicrographic Methods

A simple technique for obtaining correlation length information from a surface is to appropriately analyze a photograph of the surface. Often, a microscope should be used to expand the details of the surface. This can be done with an optical microscope or with a scanning electron microscope. In either case, the resulting photograph is called a photomicrograph. If a scanning electron microscope is used for a non-metallic surface, the sample is first coated with a metal using readily available techniques. Several surfaces were processed by a scanning electron microscope as part of this research project. It was evident that the resulting photographs could be processed using either of the techniques described below.

One technique for obtaining correlation length from a photomicrograph is an optical processing method. Two negatives (or a negative and a contact positive) of the photomicrograph are overlaid and aligned so as to match patterns identically. This sandwich is placed in a collimated beam which is focused on the other side onto a photodetector. The output of the detector may be plotted directly or digitized and stored in a computer. One negative is displaced with respect to the other in small, measured increments. At each displacement the detector output is noted. The output of such a system is proportional to the autocorrelation function of the photomicrograph. The correlation length is the value of the displacement at which the

detector output is 10% of its peak value. Obviously, one has to properly account for the magnification factor used in originally recording the photomicrograph. This technique has been used previously by the authors with a minimum of experimental difficulties.

An alternate technique for processing the photomicrograph to obtain the correlation length is to scan the photomicrograph with a microdensitometer. The output of the densitometer can be analyzed by a computer to obtain the autocorrelation function and then, by proper scaling, the correlation length. The optical technique provides parallel processing typical of optical computing. However, if a microdensitometer is available, the second technique could be used without constructing an optical correlator.

Conclusion

The most commonly used method of surface parameter measurement is mechanical profilometry. It has many limitations, particularly from a laser radar viewpoint since it traces a surface that may not be the same as the surface sensed by a laser. However, because of its widespread use, any laboratory concerned with characterizing surfaces should utilize a profilometer, preferably one that yields both rms surface roughness and correlation length. The photomicrographic technique discussed here is probably the best method of obtaining correlation length for a surface. It also provides a view of the surface that is, in many ways, more revealing to the human eye than a profilometer trace. It also more nearly approximates the surface that is sensed by a laser radar and is, therefore, recommended for use. The speckle technique of Fujii, et al. [13], is suggested as a topic for further study. Very clear experimental evidence is presented, but the theoretical explanation apparently has not been developed.

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The available statistical analyses of laser speckle from smooth surfaces have been extended to account for the effect of anisotropic surfaces on the contrast and on the autocorrelation function. Experimental results are presented for comparison with the theoretical results. For rough surfaces, an experiment is proposed for remotely determining surface roughness by using two different illuminating angles. A significant aspect of the procedure is that photographic processing has been removed from the experiment so that the technique is of interest in radar applications. An extensive literature survey of methods for measuring correlation length is reported. The various techniques are classified into three categories, profilometric, optical, and photomicrographic. The most promising procedures are discussed and two techniques are recommended for laser radar research.